Theoretical Investigation of Six-Mode Multi/Demultiplexer Based on Fused-Type Multicore Fiber Coupler

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Abstract: A six-mode \( \text{LP}_{01}/\text{LP}_{11}/\text{LP}_{21}/\text{LP}_{02} \) multi/demultiplexer based on a fused-type multicore fiber coupler is proposed, and the coupling characteristics are investigated. The multi/demultiplex operation is achieved by a phase matching between the desired mode of center core and the \( \text{LP}_{01} \) mode of the outer core in the elongated region of the fused-type multicore fiber coupler. From the numerical results based on the beam propagation method, it is found that the coupling efficiencies between the \( \text{LP}_{01} \) and \( \text{LP}_{11}/\text{LP}_{21}/\text{LP}_{02} \) modes are more than \(-0.1 \, \text{dB}\), and the crosstalk is lower than \(-20 \, \text{dB}\) at the wavelength of 1550 nm.

Index Terms: Multicore fiber, mode multi/demultiplexer (MUX/DEMUX), mode-division multiplexing (MDM).

1. Introduction
Due to the rapid increase of the Internet traffic, the increased transmission capacity of the optical communication system is highly desired. However, the transmission capacity of a standard single mode fiber (SMF) is limited around 100 Tbps due to the nonlinear optical effect and the fiber fuse phenomenon [1]. To overcome the limitation, a lot of work on space division multiplexing (SDM) have been done. Among them, a mode division multiplexing (MDM) technique using few mode fibers (FMF) as a transmission medium is currently attracting a lot of attentions and being studied because of its potential for improving transmission capacity. A mode multi/demultiplexer (MUX/DEMUX) is a key component for constructing the MDM transmission system. A number of mode MUX/DEMUXs based on free-space optics [2], photonic lantern [3], planar lightwave circuit [4], and fiber coupler (FC) have been demonstrated [5]–[8]. FC-type mode MUXs are low-loss and can be directly fused to FMFs. However, in the reported structures, a precise fiber alignment method is essential for fabricating an MUX/DEMUX with sufficient performance, and the fiber for launching higher order mode is separately fused to the main fiber, and therefore, the total length of the device becomes long. To solve these issues, we have proposed and fabricated a mode MUX based on fused type multicore FC (MCFC) for three mode
LP01 = LP11ab = LP21ab = LP02 operation, and successful three mode launch was observed [9], [10]. In our structure, since the main fiber and fibers for launching higher order mode are placed in the same fiber, the total length is shorter than those of conventional FC-type mode MUXs. In addition, the utilization of an MCFC enables precise control of the core position.

In this paper, 6 mode (LP01/LP11ab/LP21ab/LP02) MUX/DEMUX based on fused type MCFC is proposed, and the coupling characteristics are theoretically investigated. For launching the degenerate modes (LP11ab or LP21ab) separately, corresponding outer cores are placed with adequate angle with respect to the main center core. From the numerical results presented here, it is found that the coupling efficiencies for launching higher order modes are larger than −0.1 dB and the XT is lower than −20 dB for all the modes.

2. Device Structure and Operating Principle

Fig. 1 shows a (a) schematic and (b) cross-section of proposed 6 mode MUX/DEMUX based on fused type MCFC. The 6 mode MUX/DEMUX based on fused type MCFC consists of center core supporting 6 modes and five outer cores to excite higher order modes, except for the LP01 mode, to the center core. Each core has a step index profile. The relative refractive index difference and core radius of center core and outer core $i$ (=$i=1 \sim 5$) are $\Delta_i$, $r_i$, and $\Delta_i$, $r_i$, respectively. The distance between the center core and the outer core $i$ (core pitch) is $g_i$. A part of the fiber is elongated as shown in Fig. 1(a) with the length of $L$ and we assume that the transition region is linear taper with the length of $L_t$. The proposed device has five regions, namely, input, input taper, coupling (elongated), output taper, and output regions. The mode launched in the outer core is designed to satisfy a phase matching condition with the center core and coupled to the center core in the elongated region. The taper ratio is $t$, which is defined as the ratio of the core diameter of the input (or output) and the elongated regions. In the coupling region, the effective indices of LP01 mode of the outer cores 1, 2, 3, 4, and 5 are matched to that of LP11ab, LP11b, LP21a, LP21b, and LP02 modes of the center core. For LP11 modes, to excite degenerate modes separately, the position of the outer core 2 is rotated 90 degrees with respect to that of the outer core 1 [10]. As shown in Fig. 1(c), the LP11a and LP11b modes can be only launched from the outer core 1 and 2 due to the field symmetry. Similarly, outer cores 3 and 4 are placed with the 135-degree difference. Finally, the outer core 5 is placed between the core 3 and 4 since the position is the most separated from other cores.
3. Design of Center Core

The following two characteristics are important for the design of center core of 6 mode MCFC.
1) reducing the effective area ($A_{\text{eff}}$) of the LP02 mode to suppress XT to other outer cores;
2) LP31 mode, which is the next higher mode of LP02, is cut-off in the center core of the coupling region.

Characteristic 1) is important because if $A_{\text{eff}}$ of LP02 mode is large, the XT to other outer cores is increased. Fig. 2 shows $A_{\text{eff}}$ of LP02 (color map) and cut-off conditions of LP02, LP31, LP12, and LP41 modes (lines) as a function of $r_c$ and $\Delta_c$. The modal characteristics are calculated by finite-element method (FEM).

Since $A_{\text{eff}}$ of LP02 mode is rapidly increased near its cut-off, $r_c$ and $\Delta_c$ should be large (especially, $\Delta_c$) to decrease the $A_{\text{eff}}$, while keeping LP31 mode cut-off. To meet these criteria, $r_c$ and $\Delta_c$ in the coupling region are taken as $\Delta_c = 0.9\%$, $r_c/t = 6.3 \mu m$, indicated by black dot in Fig. 2. The parameters of outer cores are determined to match the effective indices of their LP01 mode to the desired higher order mode of the center core as shown in the next section. It should be noted that although maximum $\Delta_c$ is taken as 0.9% in this paper, the crosstalk may be suppressed for larger $\Delta_c$, due to tighter confinement. One can choose the value depending on the fabrication technology and the target crosstalk value.

4. Coupling Properties of 6 Mode MUX/DEMUX

About the taper ratio ($t$), if $t$ is large, the pitch in the coupling region is reduced, leading to the reduced coupling length and device size. However, if $t$ is too large, the structural difference between input and coupling region is also large. Such structural difference may cause intermodal couplings between modes having similar field distribution, such as LP01 and LP02 modes for short $L_t$. To adiabatically taper down the structure, sufficiently long $L_t$ is necessary, however, it makes the device size large. Here, we set $t = 1.4$, because in our previous works [9], [10], it was experimentally confirmed that LP01 mode in the center core is adiabatically transformed to LP01 in the coupling region. The next task is to determine the outer core parameters to match the effective indices of LP01 mode of outer cores to that of corresponding higher order modes of center core.

For $t = 1.4$, the center core radius before the elongation is $r_c = 8.82 \mu m$. Fig. 3 shows the outer core parameters, $\Delta_i$, $r_i$, at which the phase matching condition between LP01 mode of the outer core and the desired higher order mode of the center core is satisfied. Solid and dashed line correspond to the fiber before and after elongation. Fig. 4 shows the coupling length in the coupling region as a function of core pitch for outer cores 1, 3, and 5. In Fig. 4, the results are plotted for two values of $\Delta_i$ for each core. For each curve, $r_i$ is taken from Fig. 3 to satisfy the phase matching condition for corresponding $\Delta_i$. In Figs. 3 and 4, peach, blue and orange lines...
indicate the core parameters of outer cores 1, 2, outer cores 3, 4 and outer core 5, respectively. From Fig. 4, the coupling lengths between the center and outer cores can be adjusted by changing $\Delta_1$, $r_i$, and $g_i$, and we can make three coupling lengths the same. Although one can select outer core parameters freely from the solid lines of Fig. 3, here, as a one example, parameters shown by black dots in Fig. 3 are selected for the outer cores. Namely, for outer cores 1 and 2, $\Delta_{1,2} = 0.9\%$, $r_{1,2} = 4.81 \, \mu m$, for outer cores 3 and 4, $\Delta_{3,4} = 0.7\%$, $r_{3,4} = 3.85 \, \mu m$, and for outer core 5, $\Delta_5 = 0.6\%$, $r_5 = 3.78 \, \mu m$. Fig. 5 shows effective index ($n_{\text{eff}}$) of the outer core 1 as a function of $r_i/t$. For $\Delta_1 = 0.9\%$, $r_1$ is 4.81 $\mu m$, for $\Delta_1 = 0.8\%$, $r_1$ is 5.94 $\mu m$, and for $\Delta_1 = 0.7\%$, $r_1$ is 8.09 $\mu m$. From Fig. 5, $r_i$ dependence of $n_{\text{eff}}$ is larger for large $\Delta$. The dependence affects the core parameter tolerance of the device, as shown later in Fig. 8.
Fig. 6. $L_t$ and $L$ dependence of the coupling efficiencies of the desired mode in the center core at the wavelength of 1550 nm calculated by BPM for (a) the structure (1) and (b) the structure (2). The coupling efficiencies for LP$_{11}$, LP$_{21}$, and LP$_{02}$ modes are denoted by red, blue, and orange lines, respectively.

TABLE 1

<table>
<thead>
<tr>
<th>Structures</th>
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<th>(2)</th>
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<tr>
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<td>$g_{3,4}$ [µm]</td>
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<td>21.0</td>
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<td>$L$ [mm]</td>
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Fig. 7. Modal power variations when the light is launched from the outer cores 1, 3, and 5 for (a) the structure (1) and (b) the structure (2).

Fig. 6 shows $L_t$ and $L$ dependence of the coupling efficiencies of the desired mode in the center core at the wavelength of 1550 nm calculated by BPM [11], [12]. In Fig. 6(a), $g_{1,2} = 19.2$ µm, $g_{3,4} = 20.6$ µm, and $g_5 = 21.3$ µm [see structure (1)] and in (b), $g_{1,2} = 19.5$ µm, $g_{3,4} = 21.0$ µm, and $g_5 = 21.8$ µm [structure (2)]. They are summarized in Table 1. The coupling efficiencies for LP$_{11}$, LP$_{21}$, and LP$_{02}$ modes are denoted by red, blue, and orange lines. In the region surrounded by the same color lines, the coupling efficiencies are larger than −0.2 dB. The coupling efficiency is defined as the ratio of desired mode power from the output of the center core and launched power in the corresponding outer core. For each structure, there are regions that the coupling efficiencies is larger than −0.2 dB for all the modes. The red dots in Fig. 6 show the combination of $L$ and $L_t$, at which the coupling efficiencies for all the modes are large and the values are also summarized in Table 1. Fig. 7 shows the modal power variations when the light is launched from the outer cores 1, 3, and 5. Filled bars are the modal output powers from the center core, and
hatched bars are for the outer cores. For example, if the input core is the outer core 1, the output of LP\(_{11}\) mode in the center core (filled purple bar) should be large. Other filled bars show the XT in the center core and hatched bars show the XT in the outer cores. In this case, the purple hatched bar corresponds to the remaining power in the launched core. From the Figure, when the light is launched from the outer core 3 (LP\(_{21a}\) is launched in the center core), the XT to the outer core 5 is relatively large. However, by choosing appropriate geometrical parameters, it is possible to suppress all the XT below −20 dB with the large coupling efficiencies larger than −0.1 dB as shown in Fig. 7(b). Fig. 8(a) and (b) show the modal power variations when the light is launched from the center core (demultiplexing operation) for structures (1) and (2). In the horizontal axis, the name of mode exhibits the inputted mode in the center core. The definitions of filled and hatched bars are the same as in Fig. 7. The demultiplexing operation including a and b modes are clearly demonstrated. For structure (2), the modal XT value is lower than −20 dB for all modes as in Fig. 7(b). Table 2 shows electric field distributions in the input and output sections for the structure (2) calculated by BPM. From Table 2, coupling to the desired mode of the center core can be seen when LP\(_{01}\) mode is launched in each outer core, indicating that 6 mode including degenerated modes can be multi/demultiplexed selectively.

Fig. 9 shows wavelength and core radius dependence of the coupling efficiencies of (a) LP\(_{11}\), (b) LP\(_{21}\), and (c) LP\(_{02}\) modes for the structure (2). For each mode, the coupling spectra are calculated for the outer core radius of \(r_i = 0.05\) μm. From Fig. 9, for the exact design parameters, the coupling efficiencies of LP\(_{11}\), LP\(_{21}\), LP\(_{02}\) modes are more than −0.4 dB, −5.2 dB, and −7.6 dB in the entire C-band. The wavelength dependence is small for LP\(_{11}\) mode due to the small \(g_i\). If the value of \(r_i\) is shifted ±0.05 μm from the design parameters, the phase matching wavelength is shifted. The shift is largest for LP\(_{11}\) mode due to the large \(\Delta_i\). It should be noted that although for the outer core, parameters denoted by black dots in Fig. 3 are chosen for one example, one can choose different outer core parameters if they are phase matched to the
Fig. 9. Wavelength and core radius dependence of the coupling efficiencies of (a) LP_{11}, (b) LP_{21}, and (c) LP_{02} modes for the structure (2).

Fig. 10. Coupling efficiencies of LP_{11}, LP_{21}, and LP_{02} modes as a function of $\Delta r_1$ for the structure (2) at the wavelength of 1.55 $\mu m$.

5. Conclusion

We proposed 6 mode MUX/DEMUX based on fused type MCFC. By placing the outer core appropriately, 6 modes, including degenerate modes, can be launched separately. The coupling characteristics were thoroughly investigated based on FEM and BPM. From the numerical
results, it was found that large coupling efficiency (> −0.1 dB) with lower XT (< −20 dB) design is possible. The proposed MCFC is a promising candidate for low-loss and easy-connection mode MUX/DEMUX.

References